PB82-240292

Meteorological Potential for Urban Air Pollution in the Contiguous United States

(U.S.) National Air Pollution Control Administration, Washington, DC

Dec 70

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. REC PB82-240292
4. TITLE AND SUBTITLE METEOROLOGICAL POTENTIAL FOR URBAN AIR POLLUTION IN THE CONTIGUOUS UNITED STATES		5. REPORT DATE December 1970 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) George C. Holzworth Division of Meteorology		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Division of Meteorology National Air Pollution Control Administration Environmental Protection Agency		13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This study delineates some general but important features of the meteorological potential for air pollution in small and large cities throughout the contiguous United States. The potential is evaluated by means of a simple model of dispersion over urban areas in which theoretical concentrations are a function of mixing height, wind speed, and city size (along-wind distance across city). Mixing height and wind speed data are derived for mornings and afternoons from five years of surface and upper air measurements at 62 National Weather Service stations. Mean annual values of mixing height and wind speed as well as median annual and upper decile annual values of X/Q for 10- and 100-km cities are presented in the form of isoplethed maps. The X/Q maps show how theoretical concentrations vary between morning and afternoon, with city size, with frequency of occurrence, and from place to place. In addition, the potential for episodes with limited dispersion conditions lasting at least two days is evaluated objectively and depicted on a map by the total number of episode-days in five years.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Air Quality Models Meteorology		EPA 68A

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
	20. SECURITY CLASS *(This page)*	22. PRICE

METEOROLOGICAL POTENTIAL FOR URBAN AIR POLLUTION IN THE CONTIGUOUS UNITED STATES*

by

George C. Holzworth**
Division of Meteorology
National Air Pollution Control Administration
ENVIRONMENTAL PROTECTION AGENCY

---

* Paper No. ME-20C presented at the Second International Clean Air Congress, Washington, D.C., December 6-11, 1970.

** On assignment from National Oceanic and Atmospheric Administration, U. S. Department of Commerce.

ABSTRACT

This study delineates some general but important features of the meteorological potential for air pollution in small and large cities throughout the contiguous United States. The potential is evaluated by means of a simple model of dispersion over urban areas in which theoretical concentrations ($\bar{\chi}/\bar{Q}$) are a function of mixing height, wind speed, and city size (along-wind distance across city). Mixing height and wind speed data are derived for mornings and afternoons from five years of surface and upper air measurements at 62 National Weather Service stations. Mean annual values of mixing height and wind speed as well as median annual and upper decile annual values of $\bar{\chi}/\bar{Q}$ for 10- and 100-km cities are presented in the form of isoplethed maps. The $\bar{\chi}/\bar{Q}$ maps show how theoretical concentrations vary between morning and afternoon, with city size, with frequency of occurrence, and from place to place. In addition, the potential for episodes with limited dispersion conditions lasting at least two days is evaluated objectively and depicted on a map by the total number of episode-days in five years.

METEOROLOGICAL POTENTIAL FOR URBAN AIR POLLUTION IN THE CONTIGUOUS UNITED STATES

George C. Holzworth

INTRODUCTION

There is widespread apprehension that, largely because of air pollution, living in cities is unhealthy and is becoming more-so as cities grow and human activity increases. Thus, there is great interest in projected pollutant concentrations and in comparisons of different regions. Theoretically, such projections and comparisons may be made by modeling the interplay of pollutant emissions, atmospheric dispersion, (i.e. transport and diffusion), and pollutant transformations. At present, however, this approach is impeded by lack of sufficiently detailed information, especially on pollutant emissions and transformations. Yet, considerable foresight may be obtained by focusing on some broad aspects of atmospheric dispersion. This paper considers the meteorological potential for urban air pollution throughout the contiguous United States. Much of the material herein will be presented in detail in a forthcoming National Air Pollution Control Administration publication.[1]

CONCEPTS AND DATA

The main concept used in this study is that of the "mixing layer", which is defined as the surface-bounded layer of the atmosphere through which relatively vigorous vertical mixing occurs. Such mixing layers are largely generated by the vertical redistribution of heat transferred to the atmosphere from the ground and by turbulence created by obstacles to air flow. Ground-based mixing layers are very common over mid-latitude land areas during the day and over cities[2,3] at night. At night in rural areas they are often absent, being replaced by ground-based temperature inversions[4] in which vertical mixing is minimal. The height of the mixing layer is important in many considerations of dispersion. It is not uncommon for mixing heights over urban areas to vary diurnally by more than two orders of magnitude.

Mixing heights are seldom measured directly[5] but can be determined from the vertical distribution of temperature and the theory that in a thoroughly mixed unsaturated atmosphere the temperature lapse rate is dry adiabatic (.01°C m^{-1}). Although vertical profiles of temperature and wind are routinely measured only twice daily (0000 and 1200 GMT) throughout the United States (by the National Weather Service, NWS), mixing heights for other times may be estimated from routine temperature aloft measurements and surface temperature measurements for the appropriate times and places.

This study centers on two times, a few hours after sunrise and mid-afternoon, which roughly coincide with the usual diurnal maximum and secondary minimum concentrations, respectively, of slow-reacting pollutants in many cities. The morning (urban) mixing height is defined as the height above ground-level where the dry adiabatic extension of the morning minimum surface temperature plus 5°C intersects the vertical temperature profile observed near sunrise that morning (1200 GMT). The "plus 5°C" roughly allows for average effects of the urban heat island[6] of medium and large cities during the few hours after sunrise since meteorological measurements used in this study were made at NWS stations located in rural or suburban surroundings. The afternoon mixing height is defined as for the morning, except the afternoon maximum surface temperature is used instead of using the minimum plus 5°C. In view of the complex structure of the real atmosphere, these definitions of mixing height will be recognized as approximations particularly applicable in climatological studies.

Vertically averaged wind speeds within each morning and afternoon mixing layer were also determined. Five years (1960-1964) of daily morning and afternoon mixing heights and average wind speeds at each of 62 NWS stations (Fig. 1) were determined by high speed automatic data processing at the National Climatic Center. Monthly and seasonal averages, frequency distributions,

and episodic data were also obtained.

MEAN MIXING HEIGHTS AND WIND SPEEDS

Figure 1 shows isopleths of mean annual morning mixing heights over the contiguous United States. These heights are not intended to represent the diurnal minima over cities. Such values are probably considerably lower and likely occur near sunrise.[2] The heights in Figure 1 range from around 250 meters (m) to about 900 m with relatively high values near coastal areas and low values inland. Especially high values along the Gulf and Atlantic Coasts are due not only to warm water but also to copious quantities of water vapor which inhibit the nocturnal development of atmospheric stability near the ground. Similar influences due to frequent storm passages may also be seen in the Pacific Northwest region and eastward from the Great Lakes. Morning mixing heights for the most part do not vary greatly on a seasonal basis. Over inland regions, they are roughly 100-200 m higher in spring than the annual mean and in summer and autumn they are about 100 m lower.

Figure 2 indicates that mean annual afternoon mixing heights range from 800 m to more than 2600 m in contrast with the much more restricted morning values. Furthermore, the afternoon heights tend to be relatively high over inland regions and low in the vicinity of large bodies of water. This is opposite to the general distribution for mornings and results in comparatively small diurnal variations in mixing heights near shorelines and large

variations over inland regions. These variations can have marked effects on the characteristics of urban pollution problems. In further contrast with mornings, afternoon mixing heights display considerable differences in their seasonal upper limits which range from 1500 m in winter to more than 4 km in summer; these maxima occur over the southern Rockies as shown in Figure 2. Seasonal variations in coastal areas are not large.

Figure 3 illustrates the field of mean annual morning wind speed within the mixing layer of Figure 1. Speeds range from less than 2 m sec^{-1} to almost 8 m sec^{-1}. Annual morning speeds less than 4 m sec^{-1} occur only in the west although there is a large area in the east where speeds are less than 5 m sec^{-1}. The windiest places are the lower Plains, western Gulf Coast, Atlantic Coast, and northern Rockies. The pattern of annual morning speeds bears strong resemblance to the seasonal morning patterns and to the afternoon patterns, the main difference being that the afternoon speeds are 1-2 m sec^{-1} faster. In general, the faster speeds occur in spring, although in the northern Rockies they occur in winter. In the west the slower speeds occur in winter, while in the east they occur in summer. Maximum seasonal afternoon speeds exceed 10 m sec^{-1} and minimum seasonal morning speeds are less than 2 m sec^{-1}.

URBAN DISPERSION MODEL

While the mixing height and wind speed data are of considerable interest as presented, their usefulness can be enhanced if they are

used together in a model of dispersion over urban areas. The model used in this study is much like that of Miller and Holzworth[7] in which the city-wide average concentration $\bar{\chi}$ (g m^{-3}) normalized for city-wide average area emission rate $\bar{Q}$ (g m^{-2} sec^{-1}) is a function of the mixing height H (m), wind speed U (m sec^{-1}), and city size, i.e., along-wind distance across the city S (m). The main assumptions in the model are:

1. Steady state conditions prevail.
2. Emissions occur at ground-level and are uniform.
3. Pollutants are non-reactive.
4. Lateral diffusion can be neglected.
5. Vertical diffusion from each elemental source conforms to unstable conditions and concentrations follow a Gaussian distribution out to a defined travel time which is a function of H. Thereafter, a uniform vertical distribution of pollutant occurs due to further dispersion within the mixing layer.

In essence, the model treats the city source as a continuous series of infinitely long cross-wind line sources, much as did Lucas,[8] with pollutants confined to the mixing layer. This model includes some general and important features of dispersion over urban areas, but obviously, it greatly simplifies comprehensive modeling of the real atmosphere. The model equations, which are developed elsewhere,[1] are for two cases where pollutants from no (eq. (1)) or some (eq. (2)) elemental sources achieve a uniform vertical concentration:

$$\frac{\bar{\chi}}{\bar{Q}} = 3.994 \left(\frac{S}{U}\right)^{0.115}, \quad \text{for} \quad \frac{S}{U} \leq 0.471H^{1.130} \tag{1}$$

$$\frac{\bar{\chi}}{\bar{Q}} = 3.613H^{0.130} + \frac{S}{2HU} - \frac{0.088UH^{1.260}}{S}, \quad \text{for} \quad \frac{S}{U} \geq 0.471H^{1.130} \tag{2}$$

AVERAGE NORMALIZED CONCENTRATIONS ($\bar{\chi}/\bar{Q}$)

Using frequency tabulations of mixing height by wind speed and equations (1) and (2), cumulative frequencies of $\bar{\chi}/\bar{Q}$ for various city sizes were generated for each of the 62 data locations (Fig. 1). At each data location, the variation of $\bar{\chi}/\bar{Q}$ with city size is practically linear for cities larger than about 10 km. Figure 4 shows isopleths of median annual morning $\bar{\chi}/\bar{Q}$ values for 10- and 100-km cities. Highest $\bar{\chi}/\bar{Q}$ values are centered over Oregon where for 10-km cities a value of almost 40 sec m^{-1} is indicated. When such small cities in that area grow to 100 km, theoretical concentrations are expected to increase by a factor of about eight, to more than 300 sec m^{-1}. East of the Rockies, the median annual morning $\bar{\chi}/\bar{Q}$ values for 10-km cities vary only between 9 and 13 sec m^{-1}; for 100-km cities the values are generally three to five times greater, except along much of the Atlantic and Gulf Coasts where the factor is approximately two.

Assuming the current size of New York City is 50 km, the interpolated $\bar{\chi}/\bar{Q}$ value is 13 sec m^{-1}. When that city doubles in size, the median annual morning concentration will increase to only 19 sec m^{-1}, which is less than the 10-km value over parts of Arizona, Wyoming, Oregon, Nevada, and California. Along the southern California Coast the median annual morning $\bar{\chi}/\bar{Q}$ value for a 50-km city (about 10 km too small for Los Angeles) is 36 sec m^{-1} and is almost three times the corresponding value for New York City, but only one-fifth the value in southern Oregon. In terms of median annual morning values the meteorological potential clearly indicates substantially higher theoretical concentrations in several areas of the west than in the east, for both large and small cities. Morning $\bar{\chi}/\bar{Q}$ values are generally highest in summer and autumn.

Figure 5 shows isopleths of $\bar{\chi}/\bar{Q}$ values exceeded on 10 percent of all mornings annually. In some areas the values are much greater than on the median chart (Fig. 4) and the isopleth patterns are much more intense. For example, in the area of high upper decile concentrations extending from the northern Appalachians to Mississippi the values for 10- and 100-km cities increase by factors of around 7 and 15, respectively, over median values. About the same increases occur over Minnesota. In the western half of the country the increases are mostly by factors of 2-3 for 10-km cities and 3-4 for 100-km cities, except along the Pacific Coast where the increases are around 4 and 8, respectively. In contrast to the

median chart (Fig. 4), the upper decile chart shows that high $\bar{\chi}/\bar{Q}$ values in the east and west are about equal; values are almost as high over the upper Plains. It is interesting that the upper decile theoretical concentration for New York City (S = 50 km) is 65 sec m^{-1}, whereas a few hundred miles to the southwest over West Virginia the corresponding value is 375 sec m^{-1} and at Chicago it is about 220 sec m^{-1}. At Los Angeles the upper decile $\bar{\chi}/\bar{Q}$ value for a 50-km city is 210 sec m^{-1} and in southern Oregon it is more than 400 sec m^{-1}. Over much of Texas and Oklahoma as well as other smaller areas the upper decile $\bar{\chi}/\bar{Q}$ values are less than 200 sec m^{-1} for 100-km cities.

Figure 6 shows isopleths of median annual afternoon $\bar{\chi}/\bar{Q}$ values for 100-km cities. No isopleths are shown for 10-km cities because all values are 9 or 10 sec m^{-1}. This happens because the afternoon mixing heights are so high that pollutants are carried beyond the downwind edge of the city before a uniform vertical distribution within the mixing layer is achieved. To a large extent this is also true for 100-km cities whose range of $\bar{\chi}/\bar{Q}$ values is only 13-26 sec m^{-1}. Thus, in terms of median annual afternoon $\bar{\chi}/\bar{Q}$ values, the meteorological potential for urban air pollution varies only slightly over the contiguous United States, even for 100-km cities.

Figure 7 depicts the isopleths of upper decile annual afternoon theoretical concentrations for 10- and 100-km cities. For 10-km

cities most values are 10-15 sec m^{-1} and are only a few sec m^{-1} greater than median values; 15 sec m^{-1} is exceeded only in small areas centered in Wyoming and Oregon. Similarly for 100-km cities, most $\bar{\chi}/\bar{Q}$ values are between 20 and 50 sec m^{-1}, but 50 sec m^{-1} is exceeded in the west around peak values of 106 and 150 sec m^{-1}. Most of the relatively high afternoon concentrations occur in winter when afternoon mixing heights are usually lowest. It is only in the two aforementioned western areas where relatively high afternoon concentrations (Fig. 7) are approximately coincident with areas of relatively high morning concentrations (Figs. 4 and 5). Such a situation is clearly undesirable. Fortunately, large cities do not exist in Wyoming and Oregon where the relatively high morning and afternoon concentrations are highest.

EPISODIC OCCURRENCE OF LIMITED DISPERSION

From the daily morning and afternoon values of mixing height and wind speed, it was possible to determine the occurrence of episodes during which specified mixing height and wind speed values were not exceeded. As precipitation is not usually indicative of limited dispersion, its absence was also used as a criterion. An episode of limited dispersion was defined as follows:

1. All mixing heights 1500 m or less.
2. All mixing layer average wind speeds 4 m sec^{-1} or less.
3. No significant occurrence of precipitation during 12-hr periods covering each mixing height calculation.
4. Above conditions satisfied continuously for at least 2 days, i.e., for at least five successive mixing height and wind speed calculations.

Similar criteria to these have been used in the national air pollution potential forecasting program.[9] Figure 8 shows isopleths of the total number of episode-days during 5 years at each location. In the east, there is only a small area where the total episode-days barely exceeds 100, but in the west 100 days are exceeded at most stations and 200 days are exceeded over a large area. By far the greatest number of episode-days is 563 which occurred at San Diego, California, but for clarity the largest isopleth shown is 300. At nearby Los Angeles, total episode-days are less than half those at San Diego. This disparity exists because the criterion most often not satisfied at both locations is afternoon wind speed, and, while the average speed at both locations is near the critical value, it is slightly slower at San Diego. It is interesting that the specified conditions did not occur once in 5 years at two stations near the middle of the country.

Figure 8 also indicates that in the east, autumn is the season

in which most episode-days occurred. In the west the most common season is winter, except in the northern part where it is autumn due to the frequency of winter storms there. The meteorological potential for air pollution episodes is clearly much greater in the west than in the middle or eastern parts of the United States.

SUMMARY AND DISCUSSION

This study presents estimates of the fields of mean annual morning and afternoon mixing height and mixing layer average wind speed over the contiguous United States. At inland locations the variation between morning and afternoon mixing heights is often two to three orders of magnitude, whereas at coastal locations, the variation is commonly by a factor of less than two. Average wind speed patterns for morning and afternoon are quite similar with the afternoon speeds generally 1-2 m sec^{-1} faster. Combined effects of mixing height, wind speed, and city size on theoretical city-wide average pollutant concentrations ($\bar{\chi}/\bar{Q}$) are evaluated by means of a simple dispersion model. The results, in terms of annual data, show that $\bar{\chi}/\bar{Q}$ values are greater for large than for small cities, for mornings than for afternoons, and for less frequently occurring low values of mixing height and wind speed. However, the amount of variation with the indicated parameters is also variable from place to place. Thus, the $\bar{\chi}/\bar{Q}$ charts (Figs. 4-7) contain a considerable amount of information which has been evaluated herein mainly for

illustrative purposes. In general, the areas of relatively high $\bar{\chi}/\bar{Q}$ values, i.e., high meteorological potential, on the median charts differ considerably from corresponding areas on upper decile charts. Areas of relatively high and low theoretical concentrations are clearly delineated, indicating that, for several major United States cities plagued by air pollution, the meteorological potential is not nearly as great as in other areas. The greatest meteorological potential is indicated for areas in the west where relatively high morning $\bar{\chi}/\bar{Q}$ values coincide with relatively high afternoon values, but fortunately these areas are not heavily populated at this time. The study also indicates that morning $\bar{\chi}/\bar{Q}$ values increase with city size considerably faster than afternoon values, a fact of considerable importance in practical air pollution abatement and prevention strategies. Finally, the meteorological potential for urban air pollution episodes is shown to be considerably greater in the west than in the remainder of the contiguous United States.

REFERENCES

1. Holzworth, G.C., "Mixing Heights, Wind Speeds, and Potential for Urban Air Pollution throughout the Contiguous United States," manuscript in preparation for publication by the National Air Pollution Control Administration.

2. Clarke, J.F., "Nocturnal Urban Boundary Layer over Cincinnati, Ohio," Mon. Wea. Rev., 97, 582-589 (Aug., 1969).

3. DeMarrais, G.A., "Vertical Temperature Difference Observed over an Urban Area," Bull. Amer. Meteor. Soc., 42, 548-554 (Aug., 1961).

4. Hosler, C.R., "Low-Level Inversion Frequency in the Contiguous United States," Mon. Wea. Rev., 89, 319-339 (Sept., 1961).

5. McCaldin, R.O., and R.F. Sholtes, "Mixing Height Determinations by Means of an Instrumented Aircraft," Paper No. ME-39G presented at the Second International Clean Air Congress, Washington, D.C., December 6-11, 1970.

6. Peterson, J.T., "The Climate of Cities: A Survey of Recent Literature," U.S. Dept. of H.E.W., N.A.P.C.A. Publication No. AP-59, Raleigh, N.C. (Oct., 1969).

7. Miller, M.E. and G.C. Holzworth, "An Atmospheric Diffusion Model for Metropolitan Areas," J. Air Poll. Control Assoc., 17, 46-50 (Jan., 1967).

8. Lucas, D.H., "The Atmospheric Pollution of Cities," Int. J. Air Poll., 1, 71-86 (Oct., 1958).

9. Gross, E.M., "The National Air Pollution Potential Forecast Program," U.S. Dept. of Commerce, E.S.S.A. Tech. Memo. WBTM NMC 47, Washington, D.C. (May, 1970).

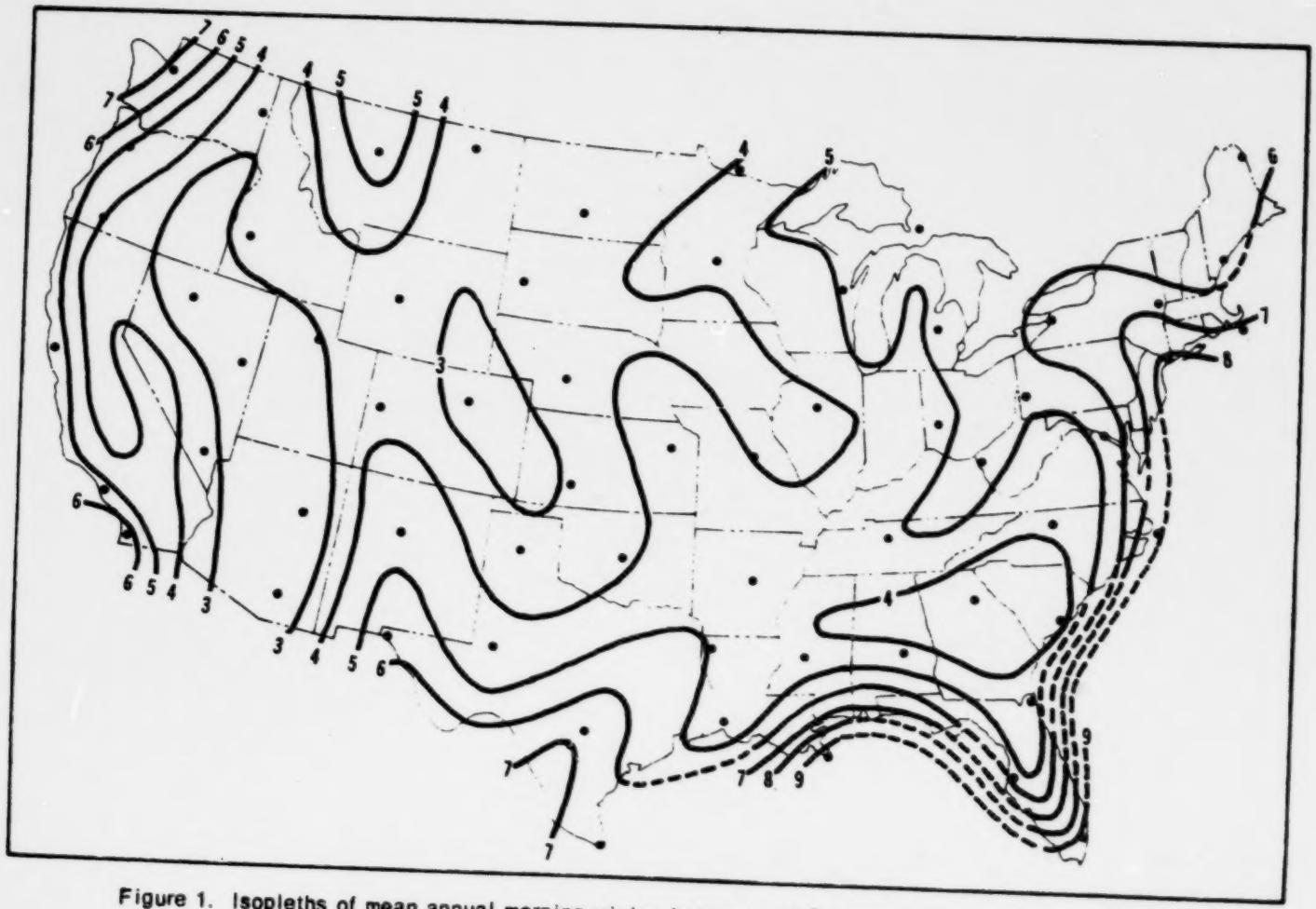

Figure 1. Isopleths of mean annual morning mixing height ($m \times 10^2$); dots indicate NWS observation locations fo: data used in this study.

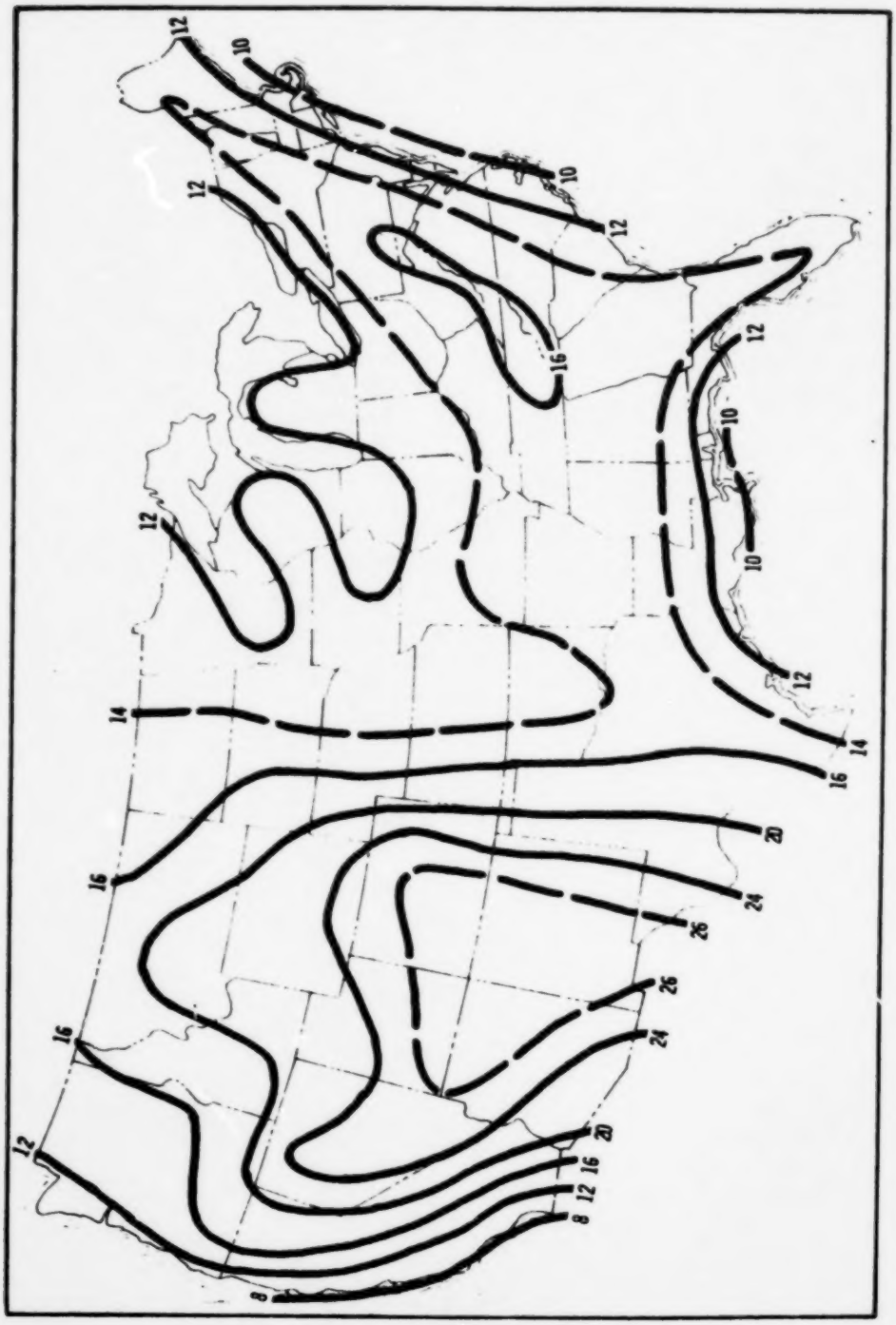

Figure 2. Isopleths of mean annual afternoon mixing height (m x 10^2).

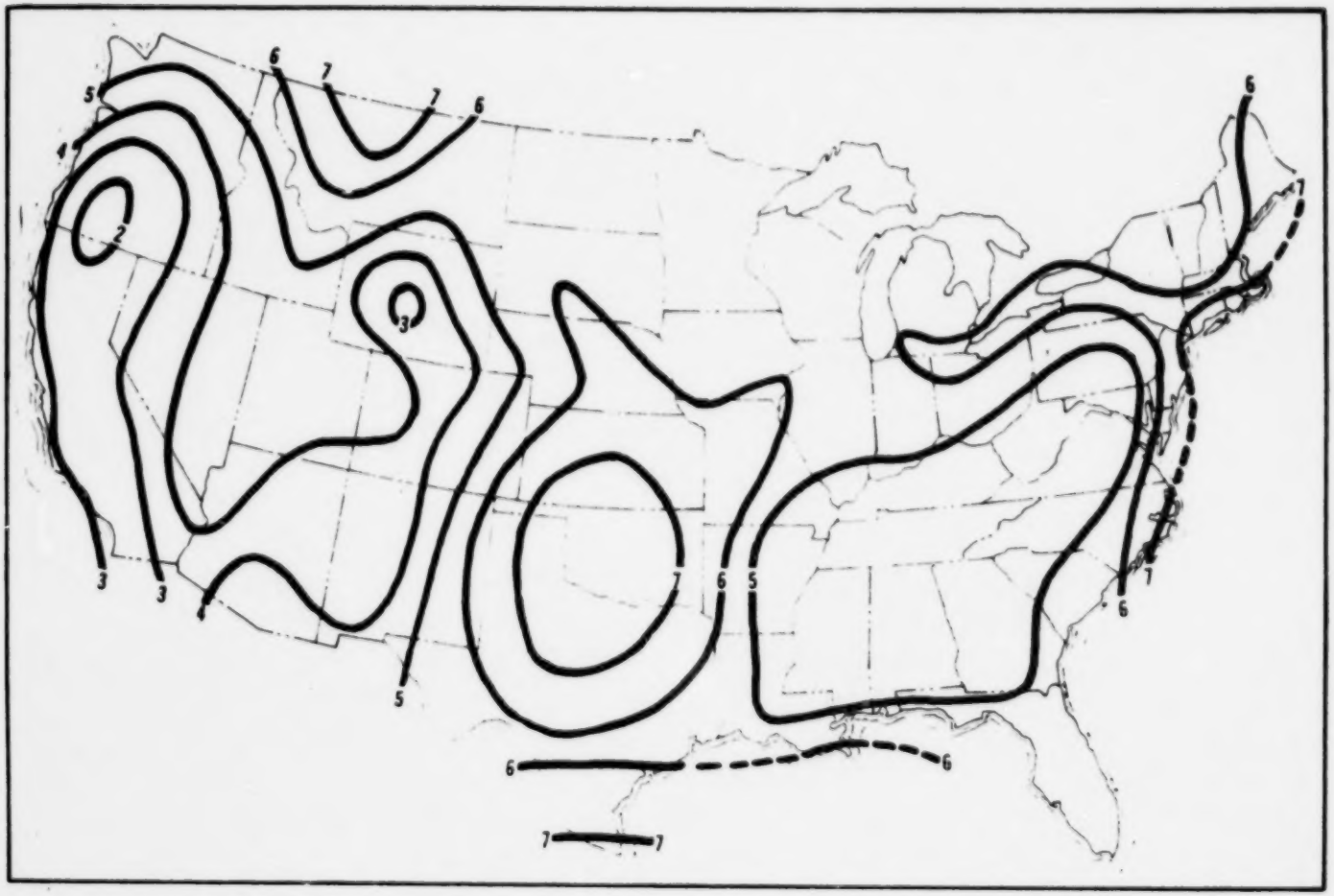

Figure 3. Isopleths of mean annual wind speed (m/sec) averaged through the morning mixing layer (Figure 1).

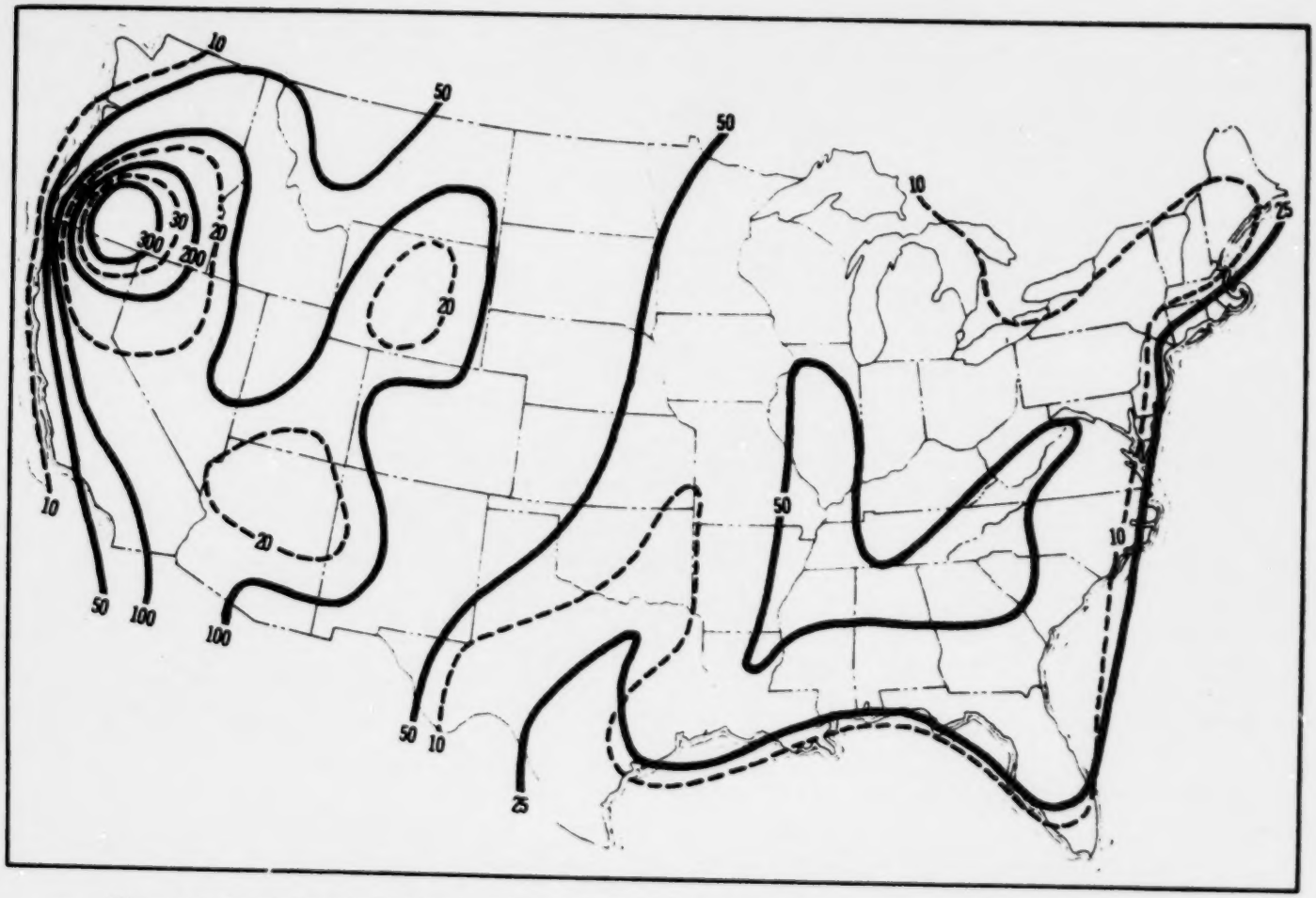

Figure 4. Isopleths of median annual morning $\bar{\chi}/\bar{Q}$ values (sec/m; see text) for 10-km (broken) and 100-km (solid) city sizes.

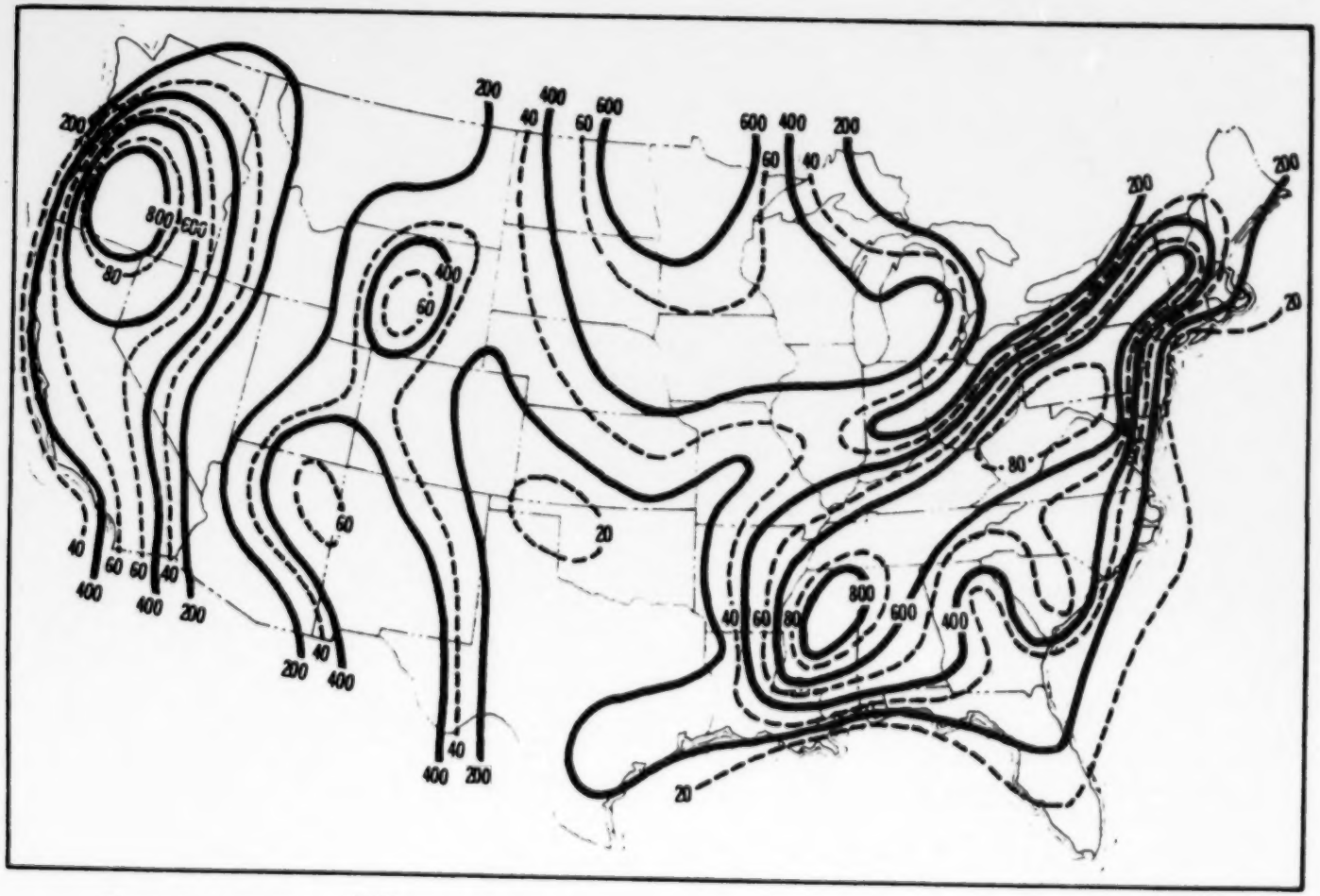

Figure 5. Isopleths of $\bar{\chi}/\bar{Q}$ values (sec/m; see text) exceeded on 10 percent of mornings annually for 10-km (broken) and 100-km (solid) city sizes.

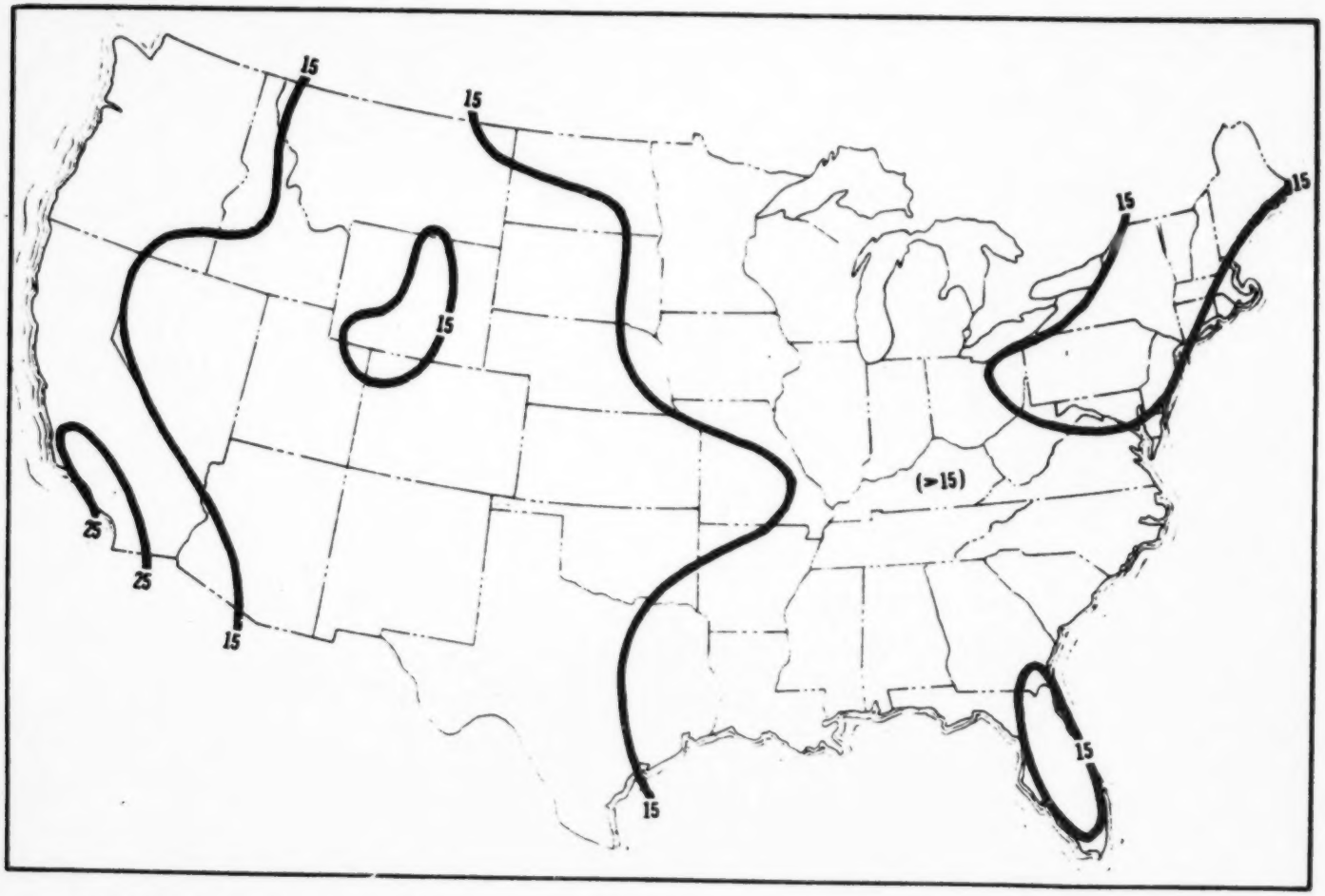

Figure 6. Isopleths of median annual afternoon $\bar{\chi}/\bar{Q}$ values (sec/m; see text) for 100-km (solid) city sizes. For 10-km cities all values are 9 or 10 sec/m.

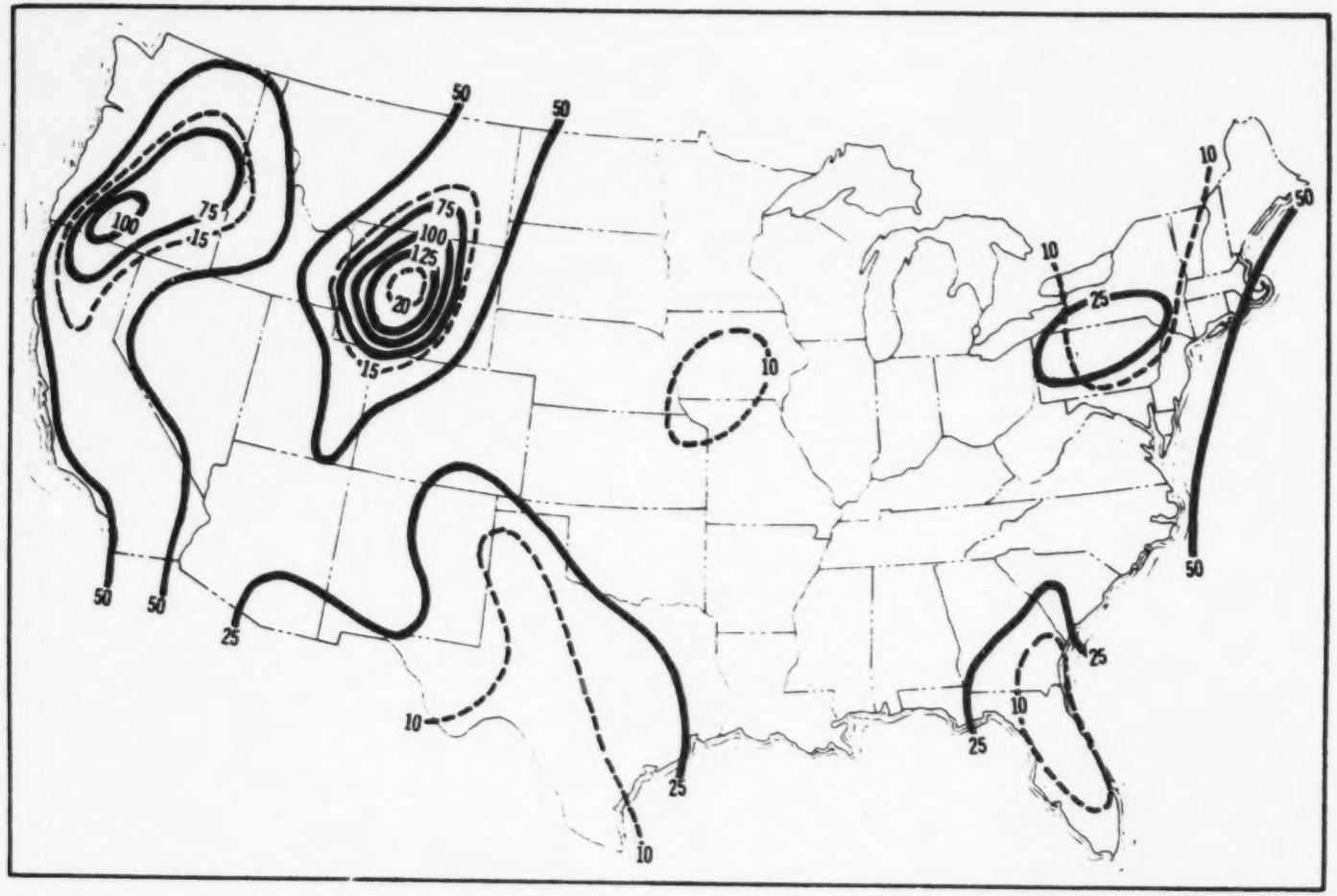

Figure 7. Isopleths of $\bar{\chi}/\bar{Q}$ values (sec/m; see text) exceeded on 10 percent of afternoons annually for 10-km (broken) and 100-km (solid) cities.

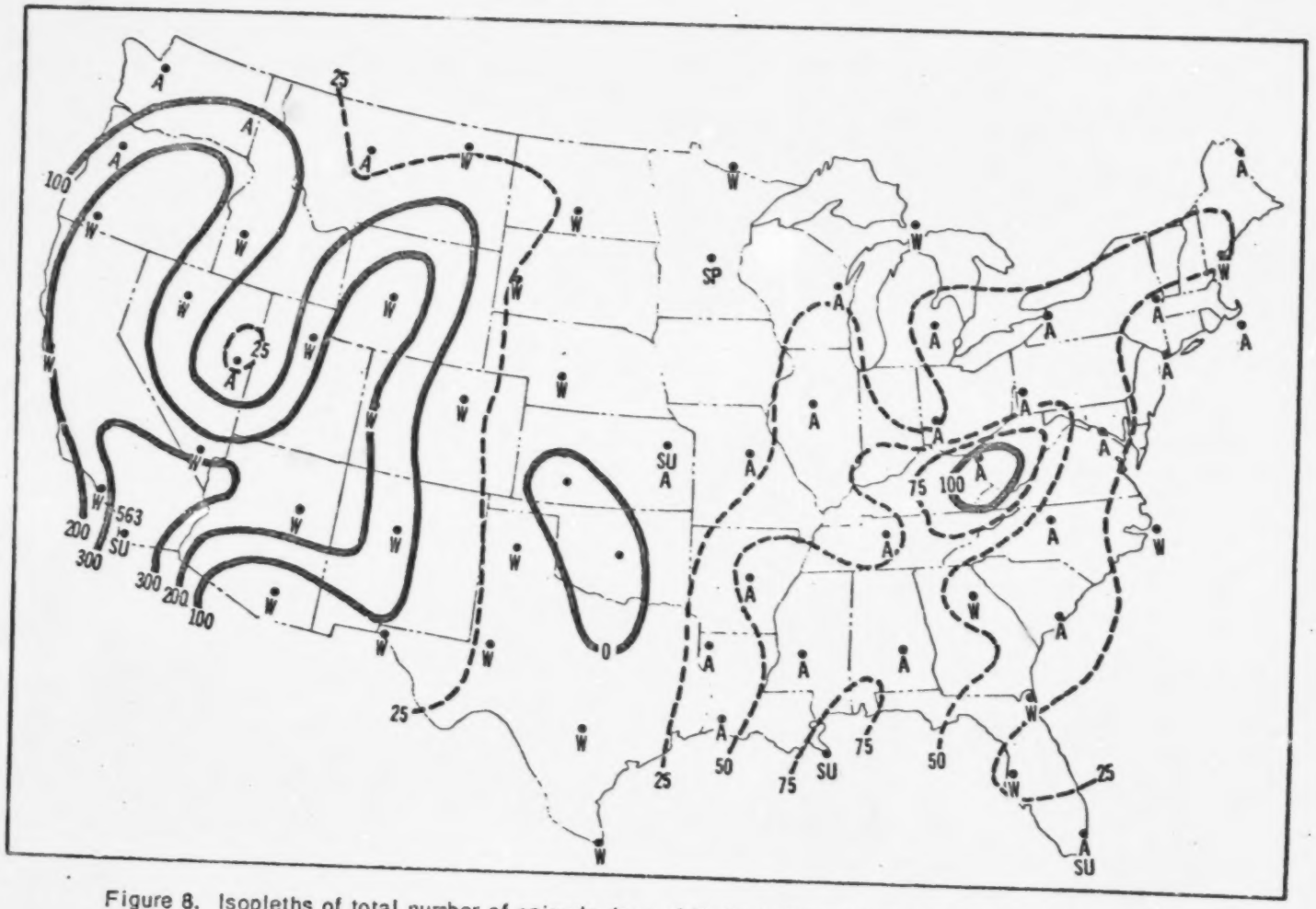

Figure 8. Isopleths of total number of episode-days of limited dispersion (see text) in 5 years; season in which most episode-days occurred at each station indicated as W (winter), SU (summer), SP (spring), or A (autumn).